NATIONAL BUREAU OF STANDARDS REPORT

5683

USE OF A D. C. AMPLIFIER AND RECORDER TO BALANCE A HIGH PRECISION RESISTANCE BRIDGE

George T. Armstrong, P. K. Wong, and L. A. Krieger
Thermodynamics Section
Heat Division

Sponsored by
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U. S. DEPARTMENT OF COMMERCE
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(j) Reversal of bridge current

Bridge sensitivity is 1.6 inches per 0.1 microvolt, or 1.6 inches per 10 microhms on reversal of current. Balance points indicated by current reversal at (f), (h), and (j) are 9.9965738, 9.9965732, 9.9965744.

ABSTRACT

By taking corrective action for electrical noise deriving from thermal agitation, alternating current pickup, and induced electrostatic charges, it has been possible to use a commercially available high gain d. c. amplifier and a recorder to balance a G-3 Mueller Bridge. Noise levels below 0. 01 microvolt peak to peak were observed with a response time of approximately five seconds. A precision of approximately two microhms was obtained in measuring a ten ohm resistor in a short series of measurements.

1. INTRODUCTION

Within certain limits the accuracy with which a voltage or a resistance can be measured depends upon the sensitivity of the voltage sensing element used to detect the unbalance of a potentiometer or Wheatstone bridge. Since the development of high precision electrical measurements, the most sensitive stable device available for measurement of small d. c. voltages has been the galvanometer. The high sensitivity galvanometer has therefore been used as an adjunct to practically all high precision potentiometers and Wheatstone bridges which require for their balance the detection of the position with null output voltage. The galvanometer is subject to limitations; it is a very fragile instrument, susceptible to vibrational disturbances, and requires a space consuming lamp and scale in order to be used. In addition, it leaves no record of its movements, and gives no signal which can be directly applied to operate another appliance. Though the latter two deficiencies can be remedied by application of photosensitive devices in one manner or another, these rapidly begin to increase the complexity of the system and do not remove the limitation of vibrations.

An alternative device for detecting the unbalance of a potentiometer or bridge measuring circuit is a high gain d. c. amplifier. Within the past several years there have been developed amplifiers of the

chopped input type[1,2] which have sufficiently high gain, low noise, good

[1] Max D. Liston, C. E. Quinn, W. E. Sergeant, G. G. Scott, Rev. Sci. Inst. 17, 198 (1946).

[2] T. M. Dauphinee and S. B. Woods, Rev. Sci. Inst. 26, 693 (1955).

zero stability and high speed of response to warrant considering as a replacement for the high sensitivity galvanometer. The application of such an instrument offers the added incentive that, in addition to providing a signal adequate for recording the bridge unbalance with a conventional potentiometric recorder, it also provides an electrical signal adaptable for use in a process control or in a feed back mechanism for automatic bridge balancing.

Experiments carried out in the past six months have been made with a view to balancing the most precise forms of Wheatstone bridge with all the accuracy attainable with a galvanometer, but using a d. c. amplifier and recorder instead. These experiments, which are described in the following report, have been successful in this respect, and in fact offer hope of greater accuracy with the instrumental assembly used than has been possible heretofore. The single qualification must be made that all measurements of the highest precision have been made on standard resistors, whose values are nearly constant over small changes of temperature. However, tests with a platinum

resistance thermometer (glass enclosed) do not show any marked increase in noise, and in sufficiently steady temperature conditions it should be possible to measure the resistance of a thermometer as accurately as that of a standard resistor.

2. INSTRUMENTATION

Three major commercially available instruments were used in the resistance measuring network. Some modifications, and a simple connecting circuit were required in order to provide a system in which each component was used at its maximum sensitivity.

a). Resistance Bridge: The bridge to be balanced was a Mueller type bridge manufactured by the Leeds and Northrup Company under the designation G-3. This bridge differs in detail but not markedly in principle from the more common G-2 Mueller bridge, which was also used successfully in some of the early tests. The former has decade dials for measuring resistance up to approximately 400 ohms in steps of 0.00001 ohm. Two rotary mercury-contact switches provide means for (a) eliminating from the measurement the resistance of lead wires to the unknown resistor, and (b) selecting the operational function to be bridge zero measurement, ratio arm adjustment, or resistance measurement. In customary use the bridge is thermostated at 35°C by a mercury thermoregulator, heater and a. c. power supply provided with the bridge. As in most bridges of this

kind, the resistance coil contacts are exposed, as are contacts for connection of the resistance element and other auxiliary apparatus. In a common use of this type of bridge in combination with a resistance thermometer to measure temperature, the thermometer current is limited by its heating effect to a few milliamperes. The sensitivity of the detector required is indicated by the fact that, using a thermometer current of one milliampere, one step of the most sensitive bridge dial causes an unbalance of 0.01 microvolt.

b). Detector: The instrument used to detect the unbalance of the resistance bridge was a Liston-Becker Model 14 breaker type d.c. amplifier. This amplifier has a voltage gain of approximately 10^7, and is claimed by the manufacturer to have a noise level not greater than twice that given by the theoretical Johnson noise formula. From a signal of 0.1 microvolt an output of approximately one volt is obtained at full gain. The amplifier is therefore adequate to drive almost any commercial recorder. The gain of the amplifier is adjustable in steps of 4 DB through 20 steps, and has also a continuous fine gain control which covers more than a single step of the coarse gain. There is also available a test signal, which may be as small as 0.1 microvolt, and a zero position adjust. In operation, d.c. entering the amplifier is mechanically chopped at 8 cps; amplified as a.c. and converted to d.c. before leaving the amplifier. The input of the amplifier was matched for a source of 50 ohms impedance.

c). Recorder: A Leeds and Northrup speedomax Model H strip chart recorder was used to record the amplifier output. This instrument had a zero center and a range of $\pm$ 5 millivolts full scale. Its speed of response was nominally 1 second for full scale deflection, its band width was approximately 1 cps, and its chart speed was one-half inch per minute. A current-adjusting-type controller was incorporated into the recorder but was not used in the experiments. A Model G Recorder having similar characteristics was used in some of the experiments and showed similar behavior. The recorders were chosen not for any special performance characteristic but because they were available for use.

The experimental assembly is shown in figure 1. A block diagram of the instruments is shown in figure 2.

3. PROBLEMS OF NOISE

3.1 Theoretical Noise Level

The noise inherent in a resistive load on account of thermal movements of the conducting particles is given by the well known formula (1) in which e^2 is the mean square thermal agitation voltage.

$$e^2 = 5.49 \times 10^{-23} \cdot Z \cdot T \cdot \Delta f \tag{1}$$

In this equation Z is the impedance and T the absolute temperature of the source and Δf is the bandwidth of the receiver. In the present

application, the impedance Z is 50 ohms, T is very nearly 300°K and Δf may be considered as a variable. Estimating for illustrative purposes a bandwidth of one cps. the quantity e is therefore $\pm 9.1 \times 10^{-4}$ microvolts. For a moderately long span of time it is found to be approximately true that the peak to peak excursions of the noise voltage exceed this quantity by a factor of 5, giving a peak noise level of 4.5×10^{-3} microvolts. It is evident that one generalization which can be drawn from the above formulation is that for a given source of noise, the effect on the receiver output fluctuations may be reduced by reducing the receiver bandwidth. This was accomplished in this case by reducing the speed of response of the recorder.

3.2 Sources of Noise Found in the Instruments

When the three instruments are combined in use it is experimentally evident that because of the low signal level desired from the source, a very serious problem arises from noise, which renders a small signal difficult to observe. From the experimental study that was carried out it was possible to trace most of the noise to several distinct causes. In each case it was possible by some device to overcome the noise problem, and in successive steps the noise was reduced to a point where the amplifier and recorder could be used effectively to balance the bridge. The sources of noise encountered may be classed as follows: (a) Random noise arising either from Johnson

noise or introduced by the amplifier. (b) 60 cycle a. c. pickup and its interaction with the chopper frequency of the amplifier. (c) Electrostatic charges induced on sensitive parts of the bridge. Each of the noise sources mentioned above will be discussed in turn in respect to its affect on the performance of the instrumental assembly, and the methods adopted to cope with it.

3. 3 Random Noise

At least two factors were involved here. As cautioned by the manufacturers, the amplifier should be operated at a relatively high output voltage, otherwise noise introduced in later stages of the amplifier becomes significant. Using a ± 5 mv. full scale recorder directly gives very unsatisfactory results because the noise introduced is at this level. More satisfactory performance is obtained when the output of the amplifier is not less than 0.5 volts.

If a sensitive recorder is to be used, the necessary adaptation to eliminate noise of this type is very simple and consists of using a resistive voltage divider in the range 100 or 200 to 1 for putting a small fraction of the total output voltage on the recorder.

When this precaution is observed, and in the absence of a. c. pickup and induced static charges, the noise as seen at full gain of the amplifier is estimated to be 0. 016 microvolts peak to peak. This is within a factor of 4 of the theoretical noise for this system, in which

a bandwidth of 1 cps is assumed. Figure 3 shows the noise under these conditions, with several different settings of the bridge. In this figure certain very large voltage excursions are noted as for example at (A). These represent effects of charges induced in the bridge by body movements as discussed in Section 3.5. In figure 3 the scale is approximately 0.024 μv/in. An approximate frequency response curve of the recorder is shown in figure 4. The bandwidth of the recorder is taken to be that frequency at which the amplitude of response has dropped to half that for a d.c. signal of the same peak voltage. By this criterion the bandwidth of the recorder is approximately 1 cps. Under such conditions and in the absence of clues as to the source of the noise a much more rapidly fruitful reduction in noise may be achieved by reducing the bandwidth of the recorder than by attempting to push the noise still closer to the theoretical lower limit.

A low pass filter was therefore introduced between the amplifier and the recorder, consisting of a large capacity electrolytic condenser, biased by a dry cell to prevent the appearance of voltage of unfavorable sign across the condenser. The connecting network between amplifier and recorder is shown in figure 5. Several condensers and a selector switch were used in the experimental work to attempt to arrive at a suitable compromise between speed of response

and noise level. The output of the amplifier is internally shunted by 500 microfarads. The noise level of the amplifier-bridge assembly is shown in figure 6 in which the effect is illustrated of 500(4), 1000(3), 2000(2), and 4000(1) microfarads, shunted by the voltage divider in this case a 2000 ohm resistor. The effectiveness of the network in reducing noise is apparent; because the time of response of the recorder becomes excessively slow with the lawger condensers, a condenser of 1000 microfarads was used with a 1000 ohm voltage divider in most of the subsequent work. Using this setting, figure 7 shows the behavior of the recorder and amplifier with input short circuited when the amplifier gain is turned to full. A 0.1 microvolt test signal is shown.

3.4 Alternating Current Pickup

A characteristic noise from in the recorder is observed in the presence of excessive a.c. (60 cycle) pickup in the bridge circuit. The noise is a regular beat with a frequency of several per second, and is produced by the presence of any nearby ironcore transformer or by alternating current within the bridge. An additional deleterious effect of this kind of pickup, when excessive, is a reduction in sensitivity of the amplifier. On this account it was found necessary to devise a way of heating the bridge without the use of the standard a.c. low voltage supply. Instead a d.c. power source and d.c. thermostat relay was devised. In figure 8 is clearly shown the

relative effects of a. c. and d. c. heater supply in their effect on the noise. Operation of the heater relay also led to a voltage pulse (A) (figure 8), and this was less pronounced in the d. c. circuit than in the a. c. circuit for a reason not ascertained. By shielding the upper surface of the bridge, and by avoiding the use of close a. c., the noise level from this source was kept close to that found in the amplifier alone.

3.5 Electrostatic and Other Sporadic Induced Voltages

A third type of noise encountered was traced to static electrical charges induced on the bridge by body movements while touching or near the bridge. Such effects appear in figure 3 as large sporadic voltage fluctuations. The one ohm and lower resistance decades of the bridge, the Normal-Reverse switch, the Zero-Ratio-Measure switch and the contact binding posts at the rear of the bridge appeared to be most strongly affected. Careful shielding of the bridge practically eliminated these effects. The shielding involved three devices, pictured in figure 1 and shown schematically in figure 9. The first involved placing a metallic cap on each of the switch handles and grounding it to provide a shorter path to ground than through the bridge elements for charges induced on the handles. The second device was a grounded metallic (aluminum) shield fitting around each switch handle shaft, and covering the area of the bridge involved.

Finally, the binding posts were completely covered. The bridge current battery and reversing switch were also enclosed in a grounded metal box.

With all precautions applied a noise level of approximately 0.01 microvolts peak to peak is observed. In figure 10 is illustrated the recorded output of the amplifier under this condition.

4. OPERATION OF THE BRIDGE

Using the d. c. amplifier and recorder, with the G-3 bridge shielded in the manner described above, the bridge can be operated in the same manner as customarily. The true null point of the bridge-chopper amplifier-recorder system can be obtained by reversing the bridge current. This has also the advantage of effectively doubling the sensitivity of the system. The amount of unbalance produced by a one step change in the most sensitive dial of the bridge is proportional to the bridge current, so that for a given noise level the bridge balance can be estimated more accurately by using a larger bridge current. For accurate thermometry, in which the heating effect of the current in the thermometer becomes measurable, an upper current limit should be imposed. In the circumstance where a 5 milliampere current can be tolerated it is estimated the balance of the bridge can be obtained to the nearest 2 microhms. In addition to balancing the bridge, the other usual functions of the bridge can be

carried out also: lead resistance can be eliminated from the measurement by use of the Normal-Reverse switch; bridge zero can be measured, and the ratio arms can be adjusted in the same manner as when a galvanometer is used.

Certain advantages of the amplifier are also apparent, principally in the form of versatility. It is possible to change very rapidly the sensitivity of the amplifier without affecting other factors of the measurement such as for example the bridge current. It is possible to have the sensitivity calibrated so that any desired sensitivity can be selected. It is also possible, by accepting a higher noise level, to increase the speed of response of the bridge unbalance indication. In the measurements shown, the speed of response is comparable to that of a high sensitivity galvanometer.

In figure 10 is shown the behavior of the bridge-amplifier-recorder combination in measuring the resistance of a standard 10 ohm resistor. The steps shown in this figure starting from the bottom are as follows: (a) steady state behavior of nearly balanced bridge, (b) 0.10 microvolt calibration voltage, (c) removal of calibration voltage, (d) change of bridge dial setting by + 0.00001 ohm, (e) restoral of bridge dial to original setting, (f) reversal of bridge current, (g) reversal of bridge current, change of dial setting by -0.00001 ohm, (h) reversal of bridge current, (i) change of dial setting by + 0.00002 ohm, reversal of current, (j) reversal of bridge current.

The sensitivity of the system in this illustration is approximately 1.6 inches per 0.1 microvolt or 1.6 inches per 10 microhms on reversal of current. The balance points as indicated by current reversal at (f), (h), and (j) are 9.9965738, 9.9965732, 9.9965744. Small changes such as these could have occurred because of temperature changes of the resistor. Assuming no change occurred, however, the reproducibility of a reading is within 2×10^{-6} ohms in this short series.

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BIBLIOGRAPHICAL CONTROL SHEET

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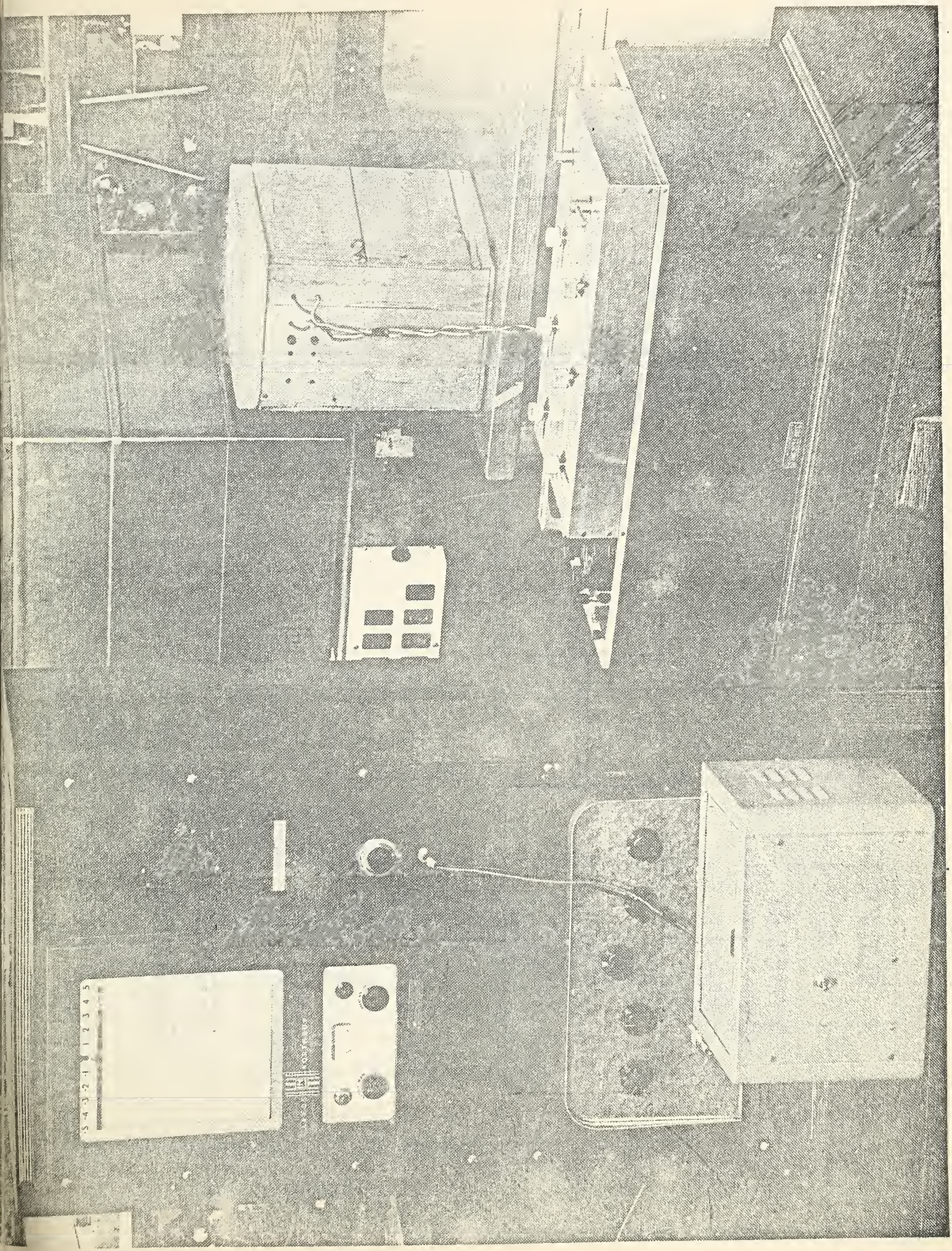
12. Abstract:

By taking corrective action for electrical noise deriving from thermal agitation, alternating current pickup, and induced electrostatic charges, it has been possible to use a commercially available high gain d.c. amplifier and a recorder to balance a G-3 Mueller Bridge. Noise levels below 0.01 microvolt peak to peak were observed with a response time of approximately five seconds. A precision of approximately two microhms was obtained in measuring a ten ohm resistor in a short series of measurements.



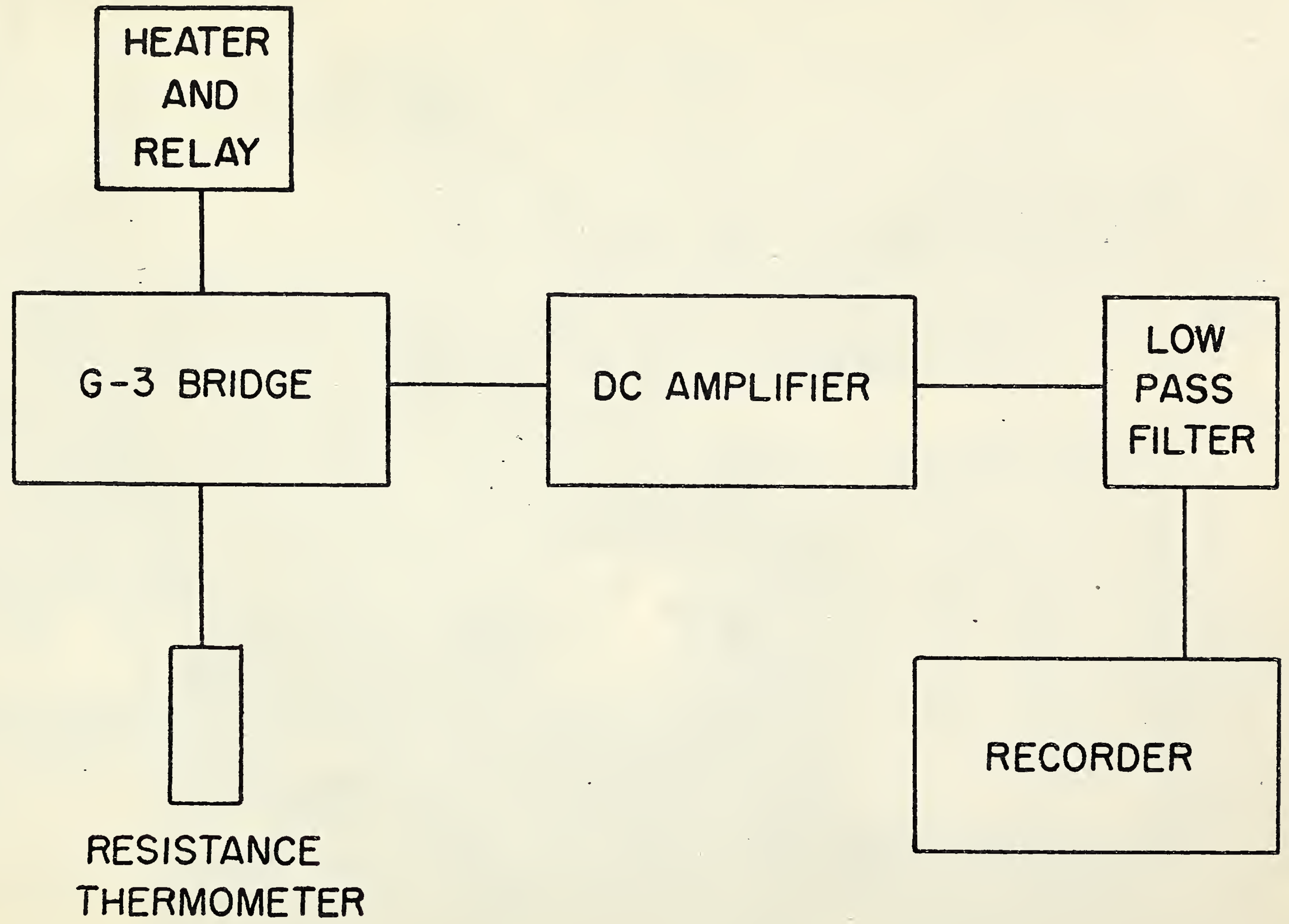


Fig. 2. Block Diagram of Resistance Measuring Assembly.

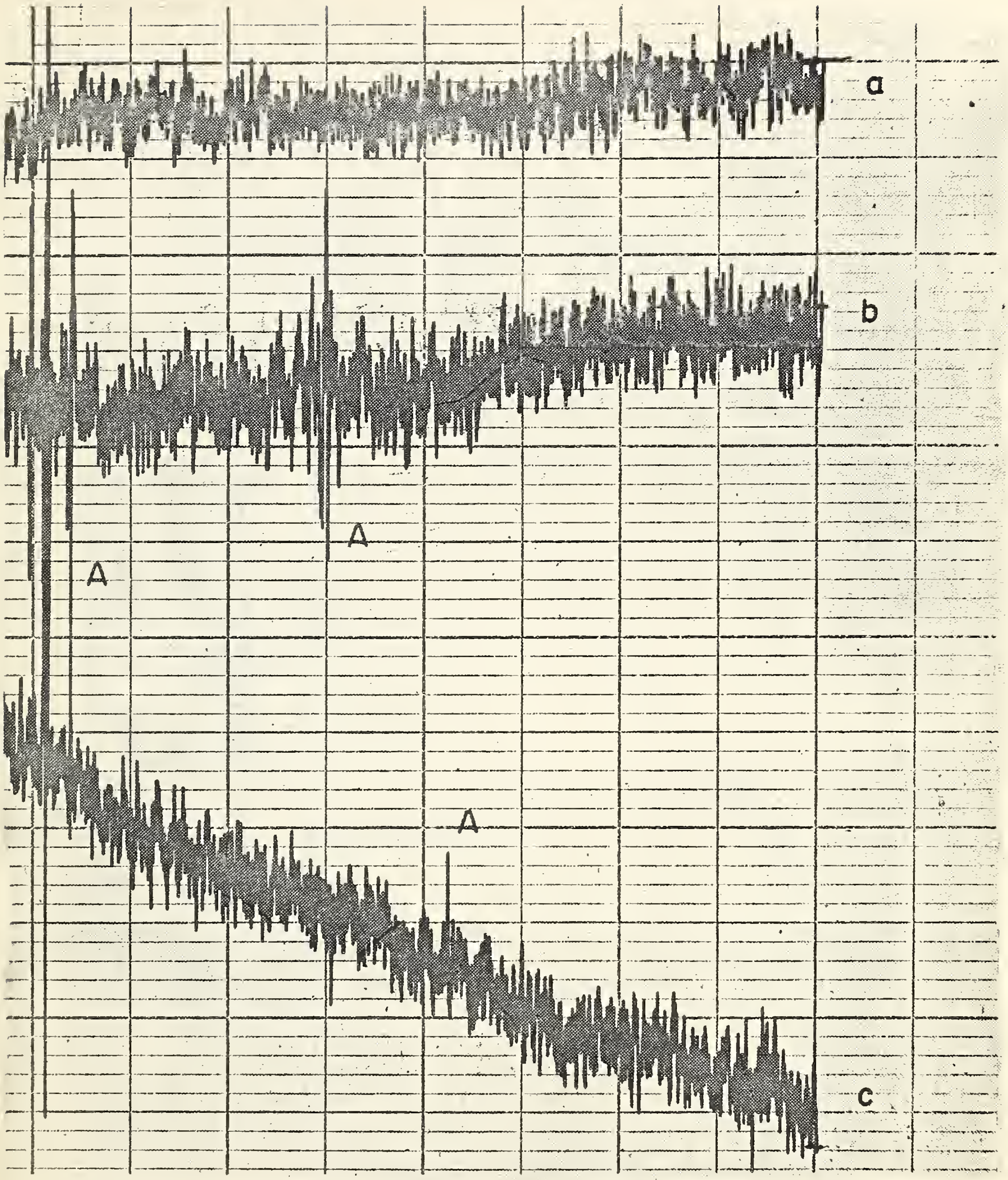


Fig. 3. Noise Level of Bridge with Recorder at
I cps Bandwith.

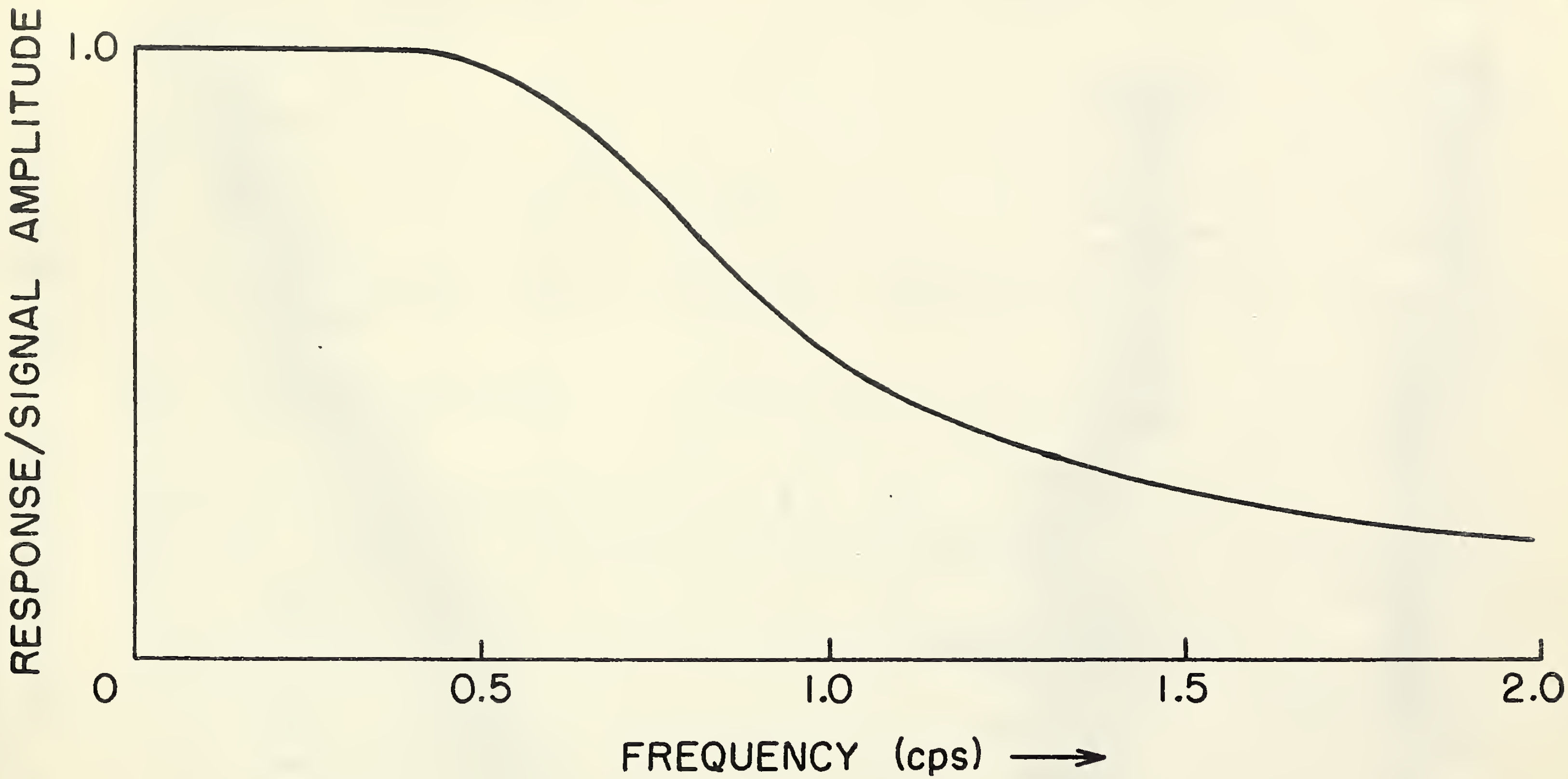


Fig. 4. Frequency Response of Recorder.

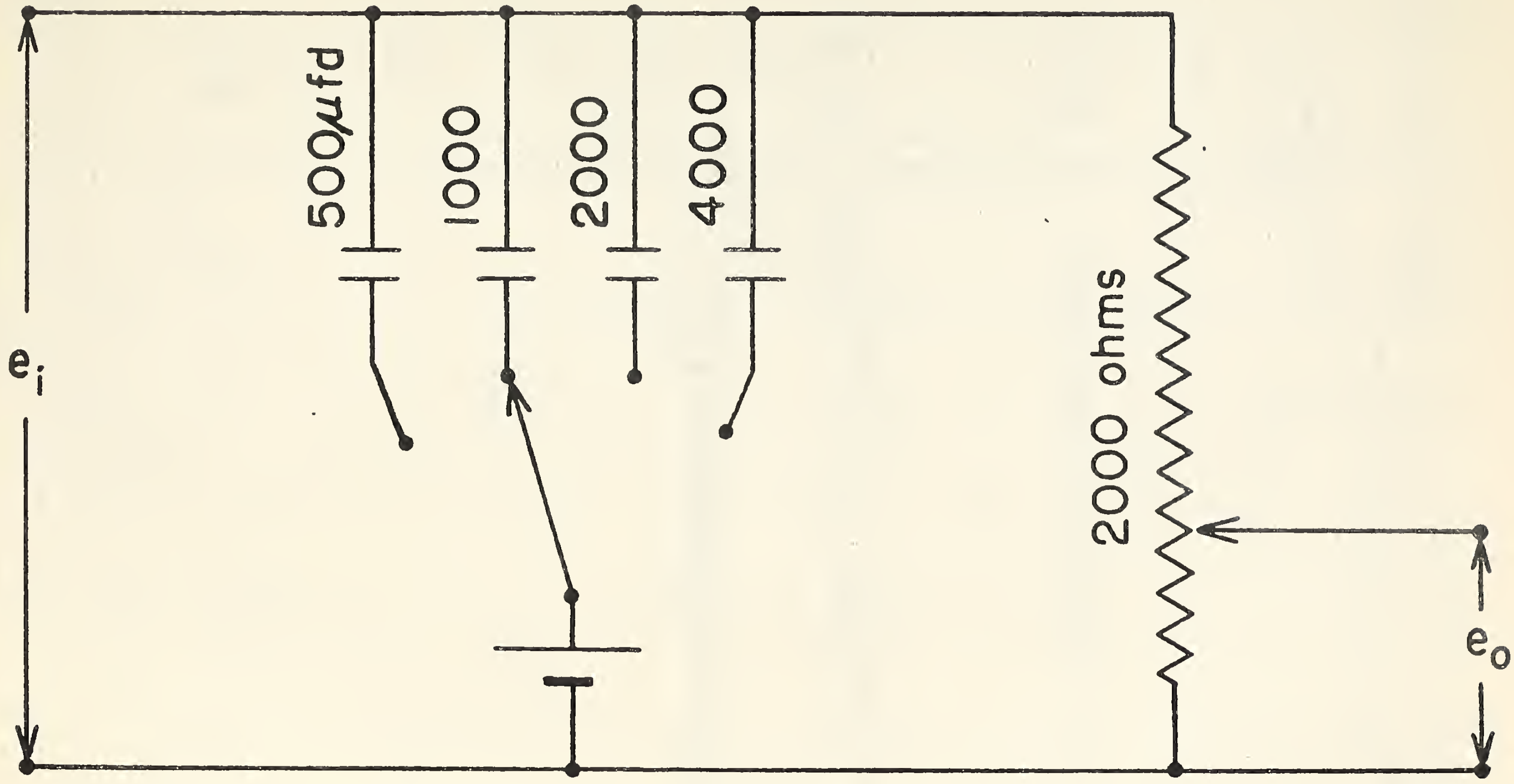


Fig. 5. Low Pass Filter.

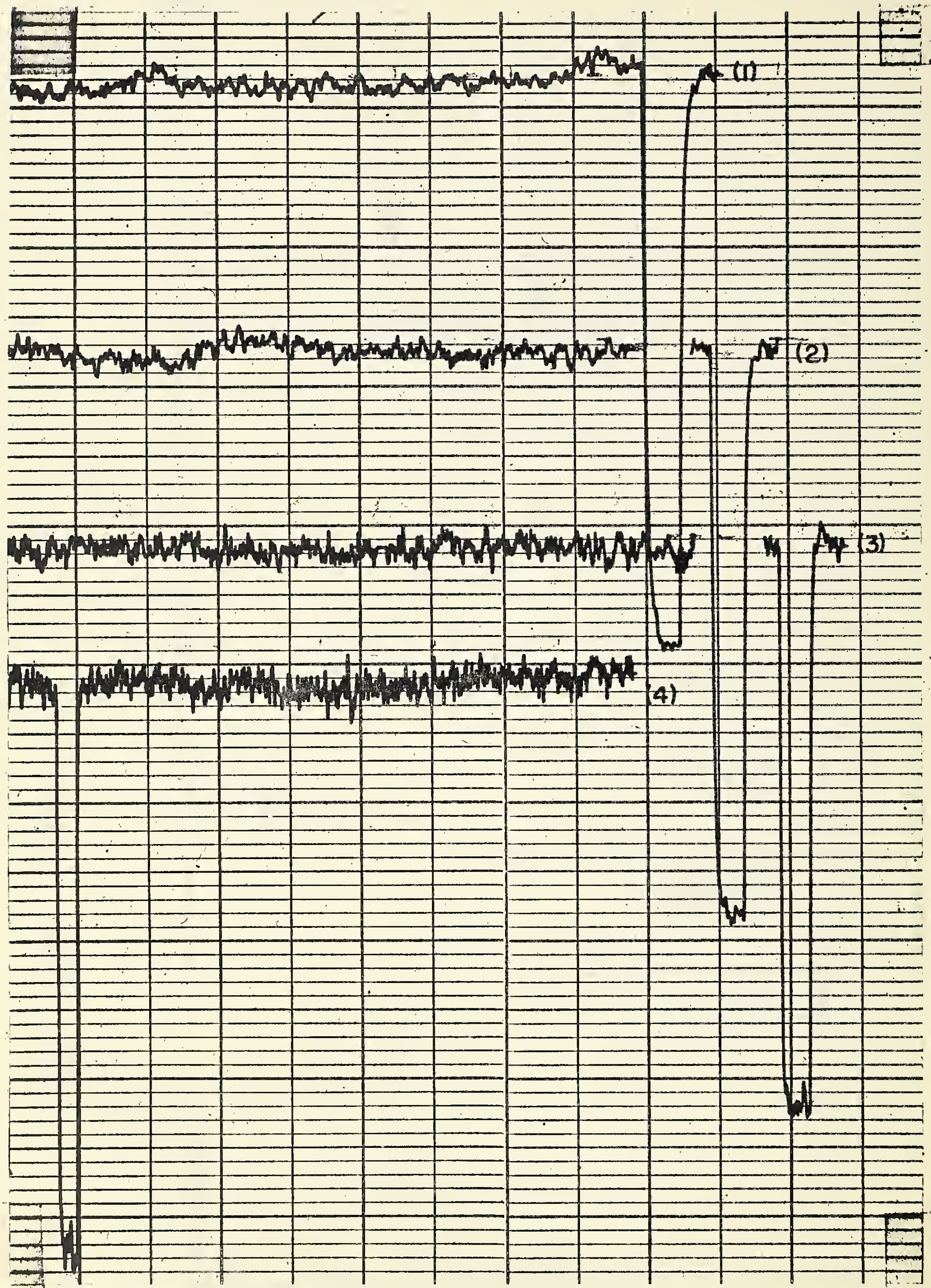


Fig. 6. Effect of Several Filters on Noise Level Record.

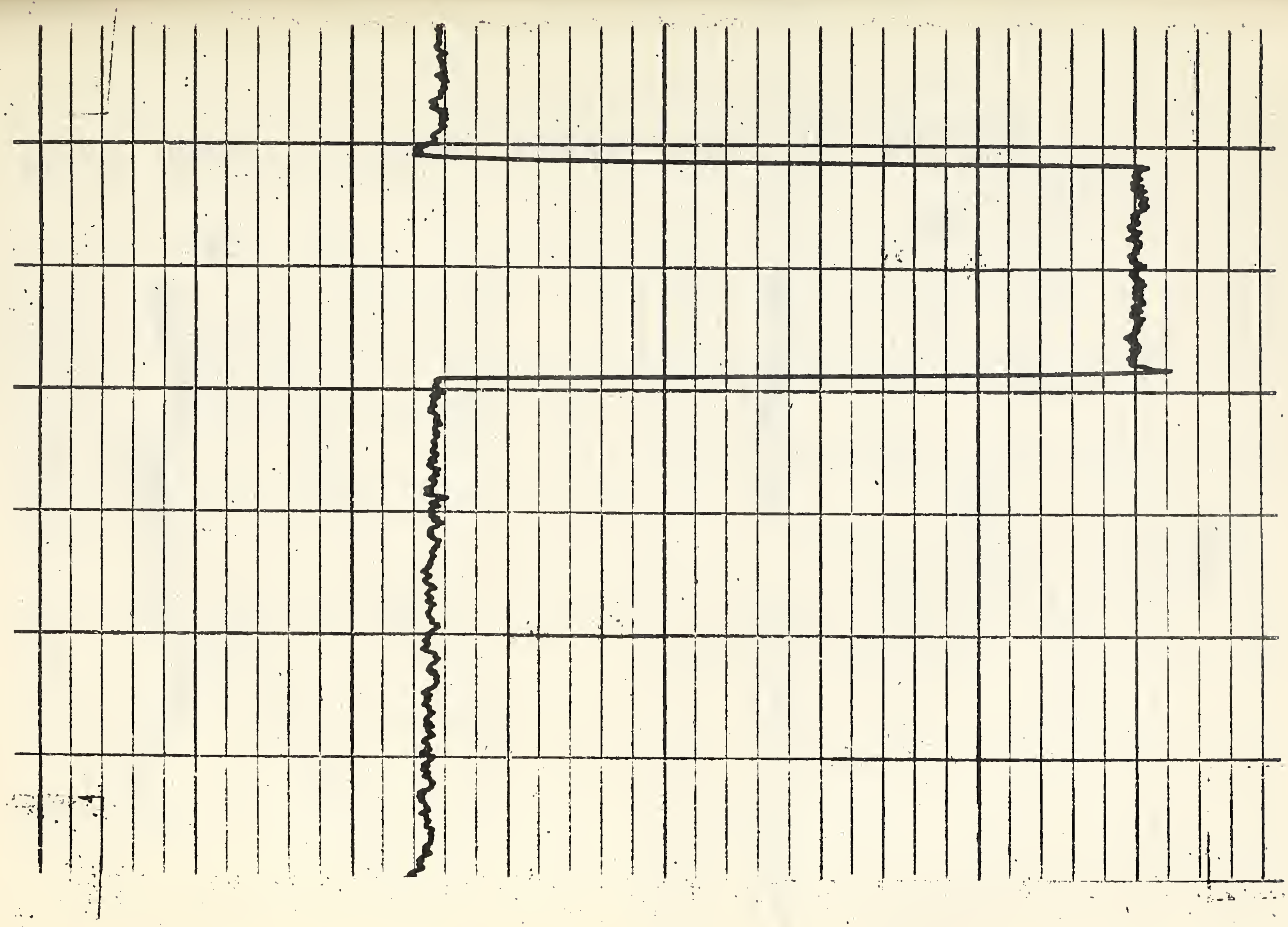
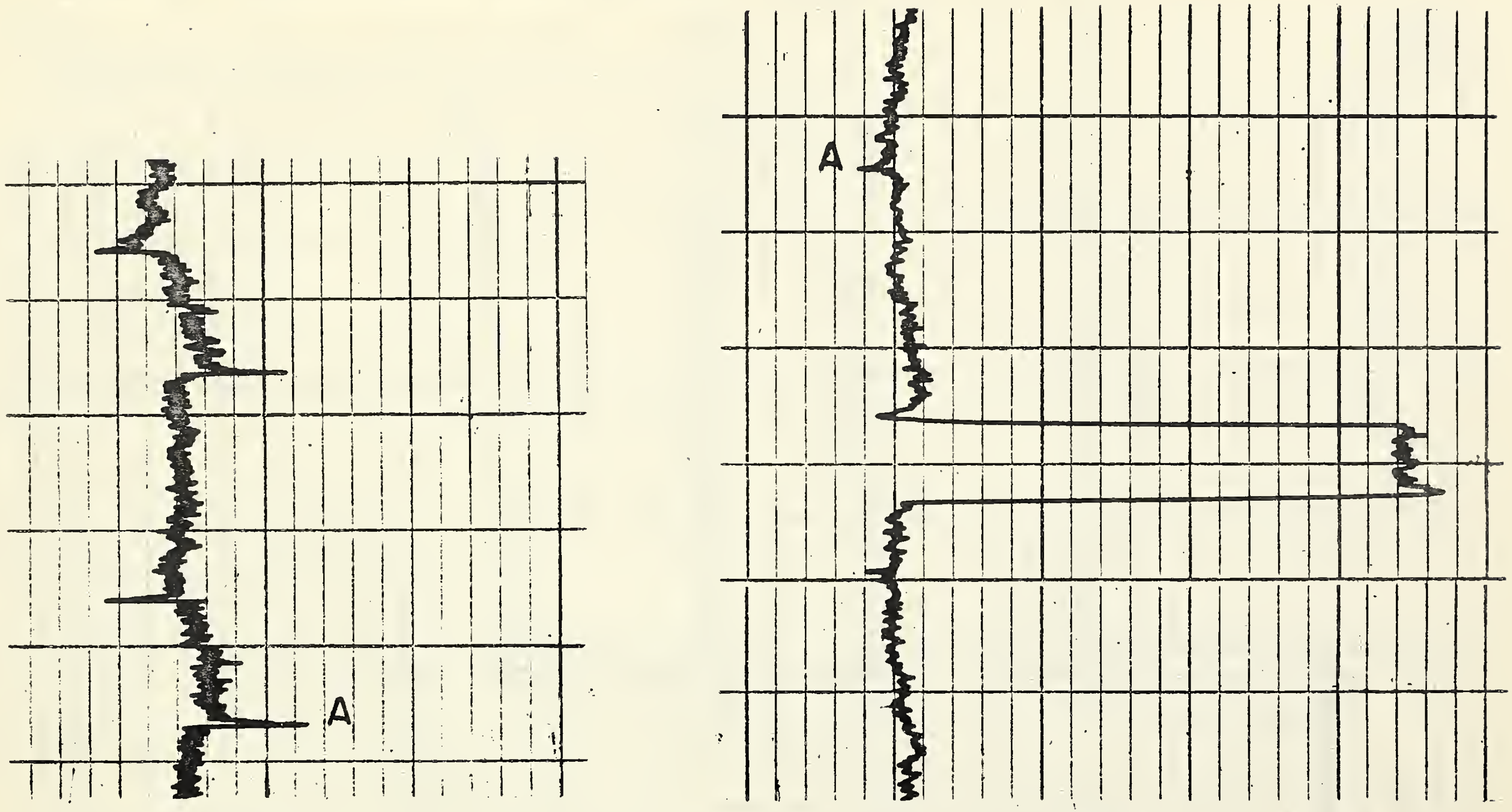
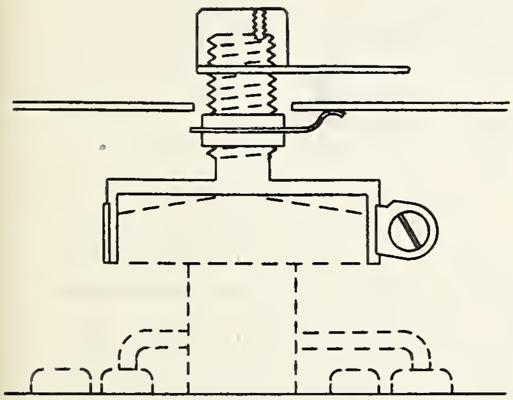


Fig. 7. Behavior of Amplifier, Filter and Recorder.

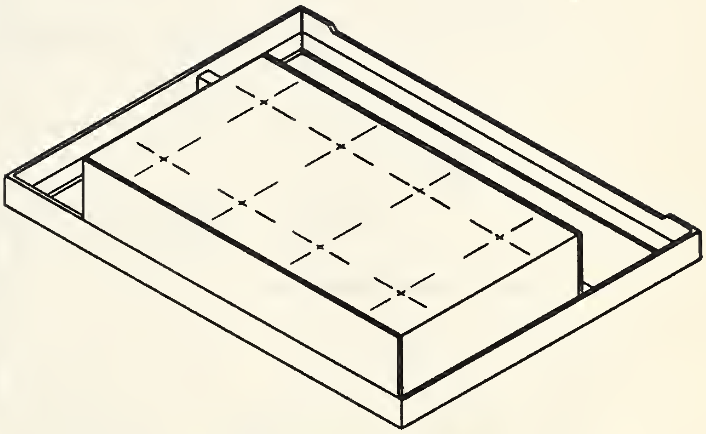


(8a) (8b)

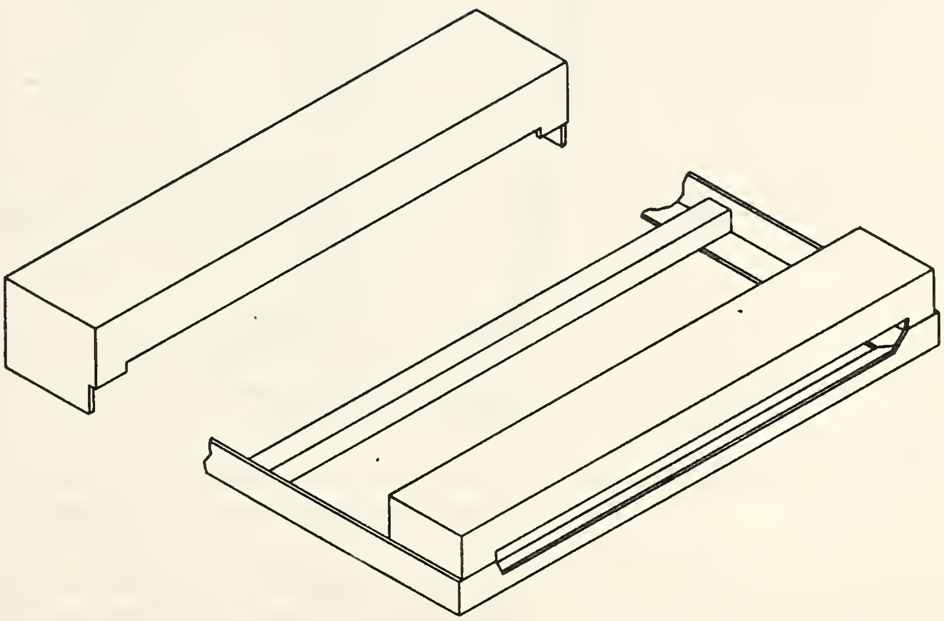
Fig. 8. Behavior of Bridge, Amplifier, Filter, and Recorder.



(9a). Decade Dial Handle Grounding Assembly.



(9b). Decade Dial Cover.



(9c). Binding Post Cover.

Fig. 9. Shielding Devices for Bridge Top.

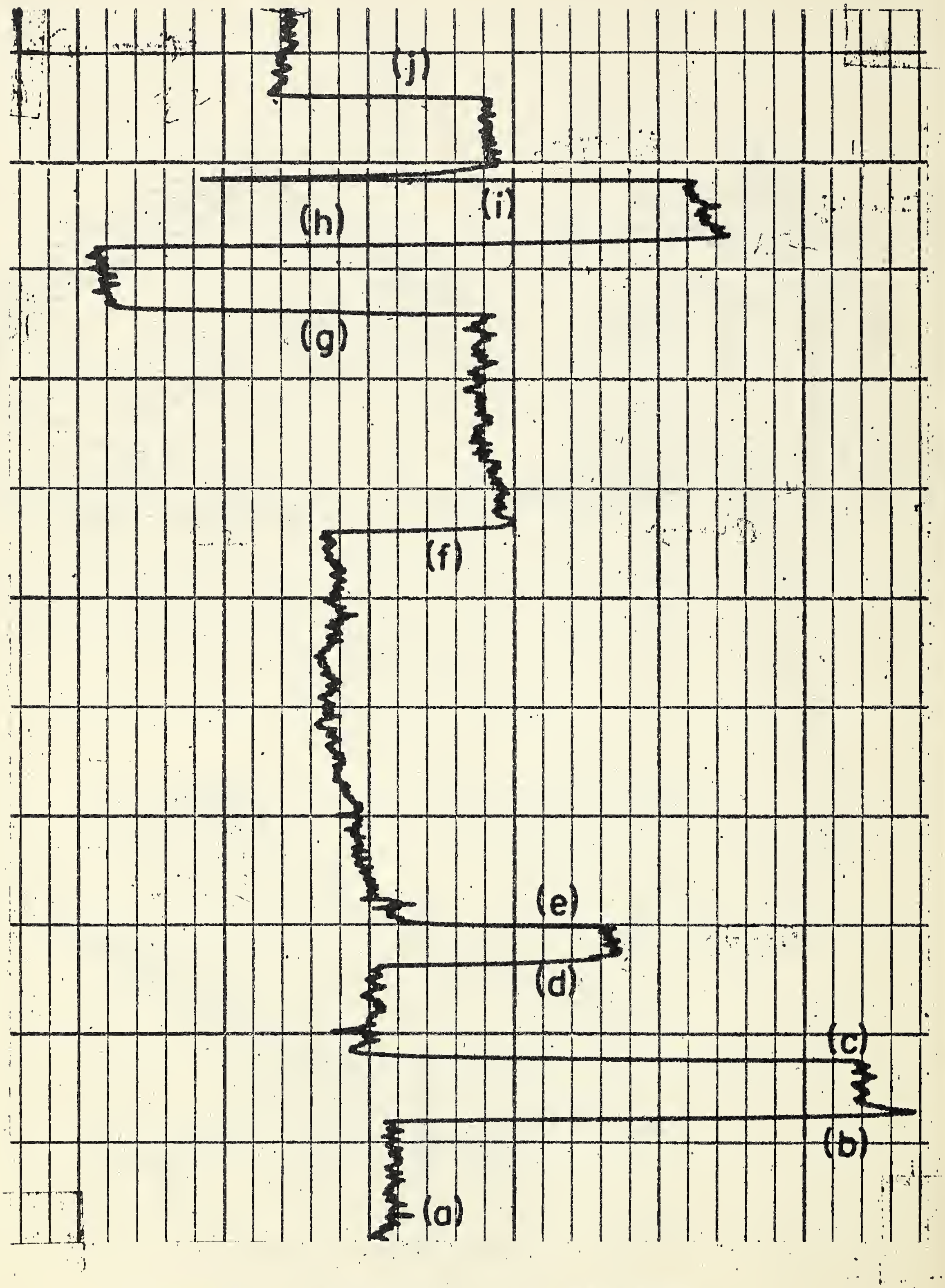


Fig. 10. Operation of Bridge.

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